

# A Planet Candidate in the Stellar Triple System HD 178911<sup>1</sup>

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## ABSTRACT

We report the detection of a low-mass companion orbiting the solar-type star HD 178911B, the distant component of the stellar triple system HD 178911. The variability of HD 178911B was first detected using radial-velocity measurements obtained with the HIRES spectrograph mounted on the 10-m Keck I telescope at the W.M. Keck Observatory (Hawaii, USA). We then started an intense radial-velocity follow up of the star with the ELODIE echelle spectrograph mounted on the 1.93-m telescope at the Observatoire de Haute-Provence (France) in order to derive its orbital solution. The detected planet candidate has an orbital period of 71.5 days and a minimum mass of  $6.3 M_{\text{Jup}}$ . We performed a spectral analysis of the star, which shows that the lithium abundances in the system are similar to those in another known planet-hosting wide binary stellar system, 16 Cyg. In

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<sup>1</sup>Based on observations made at the Observatoire de Haute-Provence (French CNRS) and at the W.M. Keck Observatory, which is operated as a scientific partnership among the Californian Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support from the W.M. Keck Foundation.

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both systems the lithium is undetected in the atmosphere of the visual secondary harboring the planetary companion, but is easily detected in the spectrum of the visual primary. We discuss this similarity and its ramifications.

*Subject headings:* binaries: general — extrasolar planets — stars: abundances  
— stars: individual (HD 178911, 16 Cyg) — techniques: radial velocities

## 1. Introduction

We report on radial-velocity measurements of HD 178911B, the fainter component of the visual binary HD 178911 (HR 7272, BD +34° 3439, ADS 12101, HIP 94075/6), which reveal the presence of a 6.3 Jovian-mass companion (minimum mass). As the brighter star of the system — HD 178911A, is actually a close binary (McAlister et al. 1987; Tokovinin et al. 2000, hereafter T00), the discovery reported here is of a planet candidate in a stellar triple system.

The variable velocity of HD 178911B was first noticed by the *G-Dwarf Planet Search* (Latham 2000). This was a reconnaissance monitoring of nearly 1000 nearby G dwarfs with the HIRES high-resolution spectrograph (Vogt et al. 1994) mounted on the 10-m Keck 1 telescope at the W.M. Keck Observatory (Hawaii, USA) to identify extrasolar planet candidates. The star was then followed up by the *ELODIE Planet Search Survey* team (Mayor & Queloz 1996, Udry, Mayor & Queloz 2001) using the ELODIE fiber-fed echelle spectrograph (Baranne et al. 1996) mounted on the Cassegrain focus of the 1.93-m telescope at the Observatoire de Haute-Provence (CNRS, France).

The ELODIE velocities were obtained by cross-correlating the observed spectra with a numerical template. The instrumental drifts were monitored and corrected using the “simultaneous Thorium-Argon technique” with dual fibers (Baranne et al. 1996). The precision achieved with this instrument for HD 178911B is of the order of  $10 \text{ m s}^{-1}$ . The HIRES instru-

mental drifts were monitored using an Iodine gas absorption cell (Marcy & Butler 1992). The radial velocities were derived from the spectra using the TODCOR code (Zucker & Mazeh 1994), a two-dimensional correlation algorithm.

The first discovery resulting from the collaboration between our teams was the determination of the orbital solution for HD 209458 (Mazeh et al. 2000) that led to the detection of the first photometric (Charbonneau et al. 2000<sup>8</sup>) and spectroscopic (Queloz et al. 2000) transits of an extrasolar planet. Recently we also detected the companion to HD 80606 and determined its orbital solution. With  $e=0.93$ , it is the most eccentric planetary orbit currently known (Naef et al. 2001).

Our observations of HD 178911B started in July 1998 with HIRES. With a velocity difference of  $63 \text{ m s}^{-1}$  in about one month between the first two measurements, it was tagged as a definite variable. This was confirmed by the next four observations in April and May 1999. In July 1999, we started an ELODIE radial-velocity follow up of 6 non-active slowly-rotating radial-velocity variable stars detected with HIRES, including HD 178911B. The combination of the two sets of radial velocities enabled us to derive the orbital solution we describe in Section 2.

In Section 3 we consider the stellar characteristics of the triple system. In particular we study the lithium abundances of the system, specially because another wide binary known to harbor a planet — 16 Cyg — exhibits a peculiar lithium abundance pattern. There the lithium seems to be depleted in the fainter stellar companion hosting the planet compared with the brighter stellar component. We find a similar phenomenon in HD 178911B. Section 4 discusses our finding by reviewing the three models proposed to explain the lithium abundance in 16 Cyg, and examines them in the context of HD 178911B. Section 5 summarizes

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<sup>8</sup>The ingress of a transit was also independently observed by Henry et al. 2000.

our findings.

## 2. Radial-velocity analysis and orbital solution

As of September 2001, we had in hand a total of 51 radial-velocity measurements for analysis: 7 from HIRES and 44 from ELODIE. The velocities are all listed in Table 1. The mean uncertainty on the velocities is of the order of  $10 \text{ m s}^{-1}$  (systematic error + photon noise) for both instruments. The HIRES velocities have an arbitrary zero point, and therefore the orbital solution presented in Table 2 includes the velocity offset  $\Delta \text{RV}_{\text{H-E}}$  between HIRES and ELODIE as an additional free parameter.

The mass given in the table —  $6.29 \pm 0.06$  Jupiter masses ( $=M_{\text{Jup}}$ ), was derived by assuming a primary mass of  $m_1 = 0.87 M_{\odot}$  for HD 178911B (T00). The uncertainty of the planet mass is much larger than the value quoted above, and it depends on the uncertainty of the primary mass, which was not given in T00. Assuming, for example, an uncertainty for  $m_1$  of 5 per cent, the error on  $m_{2,\text{min}}$  would be  $0.21 M_{\text{Jup}}$ . Adopting these values for the total mass of HD 178911B and its planet we get a semimajor axis of about 0.32 AU. The Hipparcos measurements of HD 178911B are of a very poor quality, and therefore we have not attempted to use Hipparcos to constrain the companion mass, in the way done by Zucker & Mazeh (2001).

Figure 1 shows the velocities as a function of time after shifting the HIRES data, and Figure 2 shows the residuals obtained after subtracting the fitted orbit. The phase-folded velocities are displayed in Figure 3.

### 3. Stellar properties of the wide binary

In this section we first consider previous work on the wide binary HD 178911, whose present separation is  $16''.10 \pm 0''.01$  (ESA 1997). McAlister et al. (1987) resolved the brighter component A by speckle interferometry into a  $0''.1$  binary, which was subsequently followed with radial-velocity measurements by T00. The combined spectroscopic-interferometric orbit of the close pair (T00) yielded a period of 3.55 years, an eccentricity of 0.59 and a dynamical parallax of  $25 \pm 8$  milli-arc-seconds (mas). Hipparcos (ESA 1997) reported a somewhat different parallax for HD 178911A —  $20.4 \pm 1.6$  mas, which implies a projected separation of  $790 \pm 60$  AU. Note, however, that T00 cautioned against the use of the Hipparcos parallax which was computed without considering the binary nature of A.

The radial velocity of HD 178911B was measured by T00 to be  $-40.65 \pm 0.16$  km s<sup>-1</sup>, while their orbit yielded a center-of-mass velocity for the close pair A of  $-41.01 \pm 0.03$  km s<sup>-1</sup>. This similarity, together with the high common proper motion of A and B, established the physical association of A and B. Adopting the dynamical parallax we derived a projected separation of the wide pair of  $640 \pm 210$  AU.

Using the photometry by Schoeller et al. (1998), T00 concluded that A comprises a G1-K1 pair, with masses of 1.1 and 0.79 M<sub>⊙</sub>. Their model suggested that the B component, around which the planet was discovered, is of spectral type G8V and a mass of 0.87 M<sub>⊙</sub>. T00 extracted from spectra of HD 178911 some equivalent width measurements, out of which they derived a solar metallicity for the system. The metallicity, together with the Galactic velocity of HD 178911 led them to suggest that the system belongs to a disk population of intermediate age.

We repeated the procedure used for HD 80606 (Naef et al. 2001) and used a high signal-to-noise HIRES spectrum of HD 178911B to derive its atmospheric parameters (LTE analysis) in the same way as in Santos et al. (2000). Our final iron line list consisted of 16 Fe I lines

and 2 Fe II lines. We estimated the uncertainties on the derived atmospheric parameters in the same way as in Gonzalez & Vanture (1998). The resulting atmospheric parameters are listed in Table 3.

Table 3 also includes an upper limit for the lithium abundance of HD 178911B. To derive this upper limit we summed all our 44 ELODIE spectra of HD 178911B in the  $\lambda$  6707.8 Å Li I line region. No trace of lithium was detected, and therefore a  $3\sigma$  confidence level upper limit on the equivalent width was derived. The abundance upper limit was then calculated with the curves of growth by Soderblom et al. (1993). The lithium abundance was scaled with  $\log n(\text{H}) = 12$ .

Interestingly, lithium was definitely detected in ELODIE spectra of HD 178911Aab. To show that feature, we plot in Figure 4 the relevant region of two spectra of HD 178911Aab, the co-added spectra of HD 178911B, and a spectrum of a G5 comparison star with lithium. The two spectra of HD 178911Aab were shifted according to the calculated velocity of the massive component, to align the relevant lines with those in the other spectra. One can note the absence of the Li I line in HD 178911B, and the clear presence of this line in HD 178911A. The asymmetry of the Ca I line demonstrates the binary nature of HD 178911A, as the fainter component is shifted relative to the brighter one by 0.29 Å and 0.2 Å in the two spectra. This blending of the lines of the two components of the close binary A did not allow us to perform a quantitative analysis of the lithium abundance of A. However, we adopted the value 50 mÅ as a very rough estimate for the equivalent width of the lithium line, with a probable uncertainty of 10 mÅ. This value, together with a  $T_{\text{eff}}$  estimate of 5910 K (Feltzing & Gustafsson 1998), implies  $\log n(\text{Li}) = 2.4$  for the Aa component, with a probable error of 0.1.

#### 4. The Lithium Abundance Difference of HD 178911— a Comparison with 16 Cyg

In this section we discuss the difference between the lithium abundance of HD 178911A and B. This difference is intriguing, as it reminds us of a similar difference between 16 Cyg A and B — a wide binary in which a planet was found to orbit around the B component (Cochran et al. 1997). Another intriguing similarity between the case of 16 Cyg and HD 178911 is hinted by the detection of a faint M-star companion to 16 Cyg A by Hauser & Marcy (1999), at a separation of  $3''.2$ . Turner et al. (2001) suggested the companion — 16 Cyg Ab — is not physically associated with 16 Cyg Aa, but Lloyd et al. (2001) recently claimed that its measured proper motion indicates that the Aa and Ab components are bound. Assuming this is the case, the A component of 16 Cyg, like the A component of HD 178911, is a binary, with a projected separation of about 80 AU. We summarize below the explanations suggested for the lithium abundance pattern in the case of 16 Cyg and then apply them to HD 178911.

The two components of the 16 Cyg wide binary are known to be almost identical stars, with a temperature difference smaller than 50 K (Friel et al. 1993). Naively, one would expect them to have similar lithium abundances. However, it was found (Friel et al. 1993; King et al. 1997) that the lithium abundance of 16 Cyg A is larger by at least a factor of 5 than that of B.

In general, photospheric lithium abundance in cool stars is a useful stellar evolution model diagnostic because this element is destroyed at temperatures of a few million degrees at the base of the convective zone. Although our understanding of lithium abundance evolution is far from complete, present models include burning of lithium during the early pre-main-sequence (PMS) phase of evolution, probably together with mixing material slowly over the lifetime of the star in the radiative layers below the convection zone (e.g., Ryan & Deliyannis

1995; Deliyannis et al. 2000). Therefore, the difference in the lithium abundance between the A and B components of the 16 Cyg wide binary attracted attention even before the discovery of the planet (Friel et al. 1993). Since the discovery of the planet around 16 Cyg B in 1997 quite a few studies suggested possible explanations for this difference.

King et al. (1997) commented that “it may in principle be possible for planets or associated circumstellar disks to affect a parent star’s initial angular momentum and/or its subsequent evolution and thus induce or inhibit internal mixing resulting in lithium depletion.” Cochran et al. (1997), in their planet discovery paper, were more definite in their effort to explain the low lithium abundance of 16 Cyg B. They pointed out that the angular momentum history of young solar-type stars is governed strongly by torques exerted on the star by the inner accretion disk. The general wisdom is that PMS stars with massive disks exhibit slow rotation rates resulting from the magnetic coupling to the inner disk (e.g. Choi & Herbst 1996; but see Stassun et al. 1999 for a dissenting view). Slow rotators are known to have low lithium abundance (e.g., Soderblom et al. 1993). The fact that only 16 Cyg B was found to have a planet and not the A component suggested, according to Cochran et al., that B had a more massive disk, out of which the planet was formed. The same massive disk induced slowing down of the stellar rotation at the PMS stage and therefore led to lithium depletion in its atmosphere.

Some support for this scenario has been presented by Gonzalez & Laws (2000). They pointed out that when corrected for differences in temperature, metallicity and chromospheric activity, the lithium abundances of planet-hosting stars are in general lower than normal stars. The evidence for this general trend was disputed by Ryan (2000), who claimed that the lithium abundances of planet-harboring stars are indistinguishable from those of non-planet-harboring stars of the same age, temperature and composition. He further argued that the small difference in temperature between 16 Cyg A and B (Deliyannis et al. 2000;



Laws & Gonzalez 2001) could explain the lithium abundance difference, although the  $\text{Li-T}_{\text{eff}}$  slope might be somewhat steeper in the 16 Cyg system than observed elsewhere. From this point of view the planet around B has nothing to do with the lithium abundance difference.

A completely different explanation for the lithium abundance difference between 16 Cyg A and B was suggested by Gonzalez (1998). In a paper where he invoked a pollution scenario for the *high* metallicity of the stars hosting planets, he suggested that 16 Cyg A ingested a planet that was pushed into its atmosphere by tidal interaction with the existing planet of the B component. The swallowed planet raised the lithium abundance of 16 Cyg A dramatically. Laws & Gonzalez (2001) found some support for this scenario by their finding that the iron abundance of 16 Cyg A is slightly higher than B. They argued that both the slightly higher metallicity and the large difference in the lithium abundance could be attributed to a scenario in which A swallowed a giant planet into its atmosphere. Evidence for such a process where a planet was swallowed by its host star was also found in the case of HD 82943 (Israelian et al. 2001).

To summarize, three explanations have been put forward to explain the lithium abundance difference between 16 Cyg A and B, two of which had to do with the fact that B has a planet around it, while A does not. One of the two attributed the depletion of lithium in B to the massive disk that eventually formed the planet, while the other attributed the relatively high lithium abundance of A to the ingestion of a planet by A. The third explanation was based on the temperature difference between A and B.

We can now examine the relevance of the three explanations to the HD 178911 system. Here also the lithium depletion was found in the planet-hosting star which is also the cooler star. The low lithium abundance of B could be the result of its massive disk, as the first explanation suggests. The lithium abundance difference might also be the result of the different temperatures of A and B. The value we got for the lithium abundance of B, together

with the rough estimate for A, suggest a difference of at least 1.6 in  $\log n(\text{Li})$ . The calibration of Gonzalez & Laws (2000) predicts a much smaller difference of 0.44 for the same  $T_{\text{eff}}$  difference. However, the explanation suggested by Ryan (2000) for 16 Cyg might apply here also. If we extrapolate his suggestion of a 0.33 dex decline in  $\log n(\text{Li})$  per 50 K, we get a difference of 1.72 dex for the HD 178911 system, consistent with our estimate. Then again, it is not clear whether the slope suggested by Ryan is applicable to the whole range of temperatures covered by the two components of HD 178911.

When we try to invoke the planet-ingestion scenario to produce a lithium enhancement in HD 178911A, we face some difficulties, because of the relative proximity, 3 AU, of the Aa and Ab components. The tidal forces of Ab would have disrupted any planetary orbit around Aa in a very early stage, especially under the migration hypothesis which requires the planet to form in a distance of a few AU from its parent star. However, to still hold to this scenario for HD 178911 we might try to invoke the formation of a circumbinary planet. Such a scenario is possible, although no circumbinary planet has been discovered yet (e.g. Holman & Wiegert 1999). This hypothetical planet could have migrated inwards through the standard migration mechanism, or interact with the planet of HD 178911B in the way suggested for 16 Cyg by Gonzalez (1998). At close enough distance to the binary, the resulting instability might lead to ingestion of the planet by one of the binary components. We will not face the same difficulties in 16 Cyg A, even if we accept the triple nature of 16 Cyg, since the 16 Cyg A pair is wide enough (80 AU) to allow the formation and evolution of a planet around Aa. Thus, in principle, we cannot completely rule out any of the three explanations, although the planet-ingestion seems less likely for HD 178911 as it requires some non-standard formation processes.

Interestingly, Ryan & Deliyannis (1995) suggested that binaries with sufficiently short periods might have preserved more lithium than normal, single stars. They relied on the

theory of Zahn and Bouchet (1989; but see the different approach by Mathieu and Mazeh 1988 and Goldman and Mazeh 1991) that short-period binaries, with periods shorter than 8–9 days, reached synchronization during the *early* stages of the PMS phase. At this early fully convective stage, the stellar interiors were not hot enough to destroy lithium. The depletion of lithium occurred in a later stage at the stellar interior by “angular momentum transport mixing”. Short-period tidally-locked binaries did not go through this mixing stage because of their different angular momentum evolution and therefore display high lithium abundance. Whatever the mechanism would be, it seems that the long period of the HD 178911A binary renders this argument inapplicable to our system.

## 5. Conclusion

We have shown evidence for a planet orbiting HD 178911B, at a separation of about 0.3 AU. HD 178911B and 16 Cyg B are currently the only triple systems known to harbor planets. In both cases the planet was discovered around the distant component, while the other two stars comprise a close binary.

Can there be another planet around one of the components of HD 178911A? According to the presently accepted paradigm, the short period planets have migrated from where they had formed, at a few AU (but see, e.g., Boss 1998 for an alternative). At such large distances, no planet could have survived the tidal interaction of the other star in the close pair HD 178911A. It seems that under the present paradigm the only possible planets in the close pair are circumbinary planets.

Assuming that at present there is no planet around HD 178911A, it is interesting to consider the formation of the whole HD 178911 system. Suppose that the visual binary was formed by a fragmentation event during the collapse of a molecular cloud core (e.g., Burkert

& Bodenheimer 1993). The cloud core collapsed until it was of the order of a thousand AU in diameter, at which time it fragmented into two parts. One part ended up as the close stellar pair A, while the other one formed (at least) one planet which we have discovered. It would be interesting to figure out what were the differences in the two cores that caused them to evolve on such different formation tracks, and whether the lithium abundance of A and B can shed some light on our understanding of their evolution.

We acknowledge support from the Swiss National Research Found (FNRS), the Geneva University and the French CNRS, the US-Israel Binational Science Foundation through grant 97-00460 and the Israeli Science Foundation (grant no. 40/00). We are grateful to the Observatoire de Haute-Provence for the generous time allocation. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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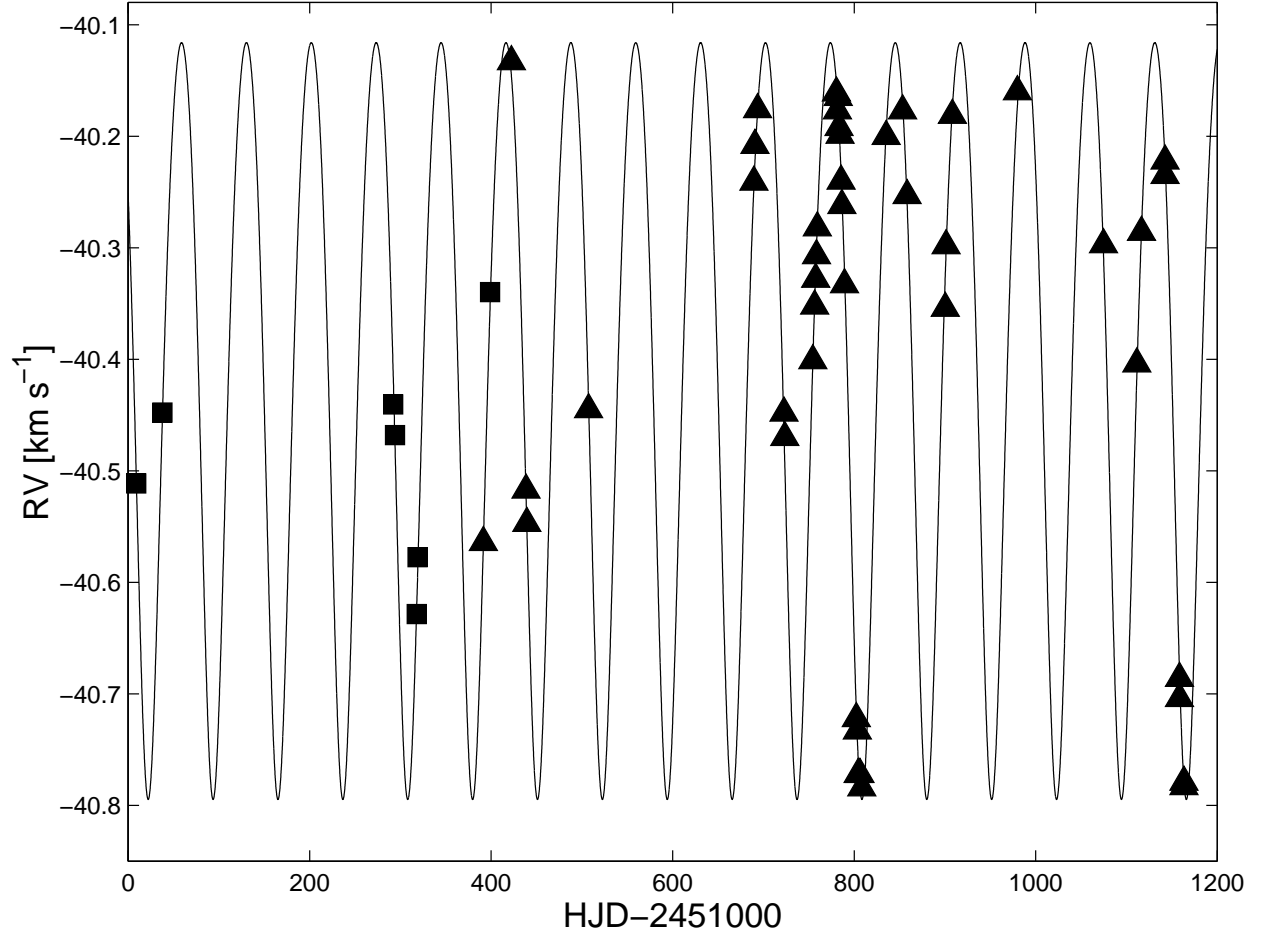


Fig. 1.— HD 178911B radial-velocity data. Triangles: ELODIE-OHP measurements. Squares: HIRES-Keck measurements.



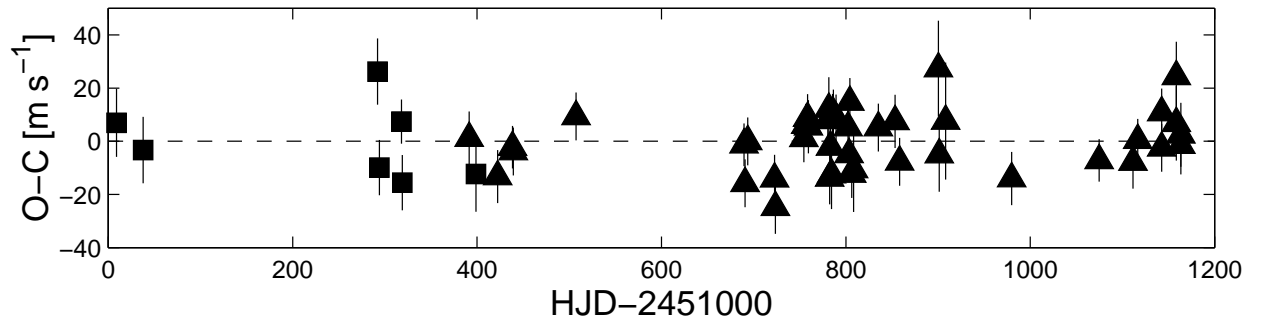


Fig. 2.— The residual radial velocities after subtracting the orbital solution. The error-bars represents the errors of the original velocities. Triangles and squares: see Figure 1.

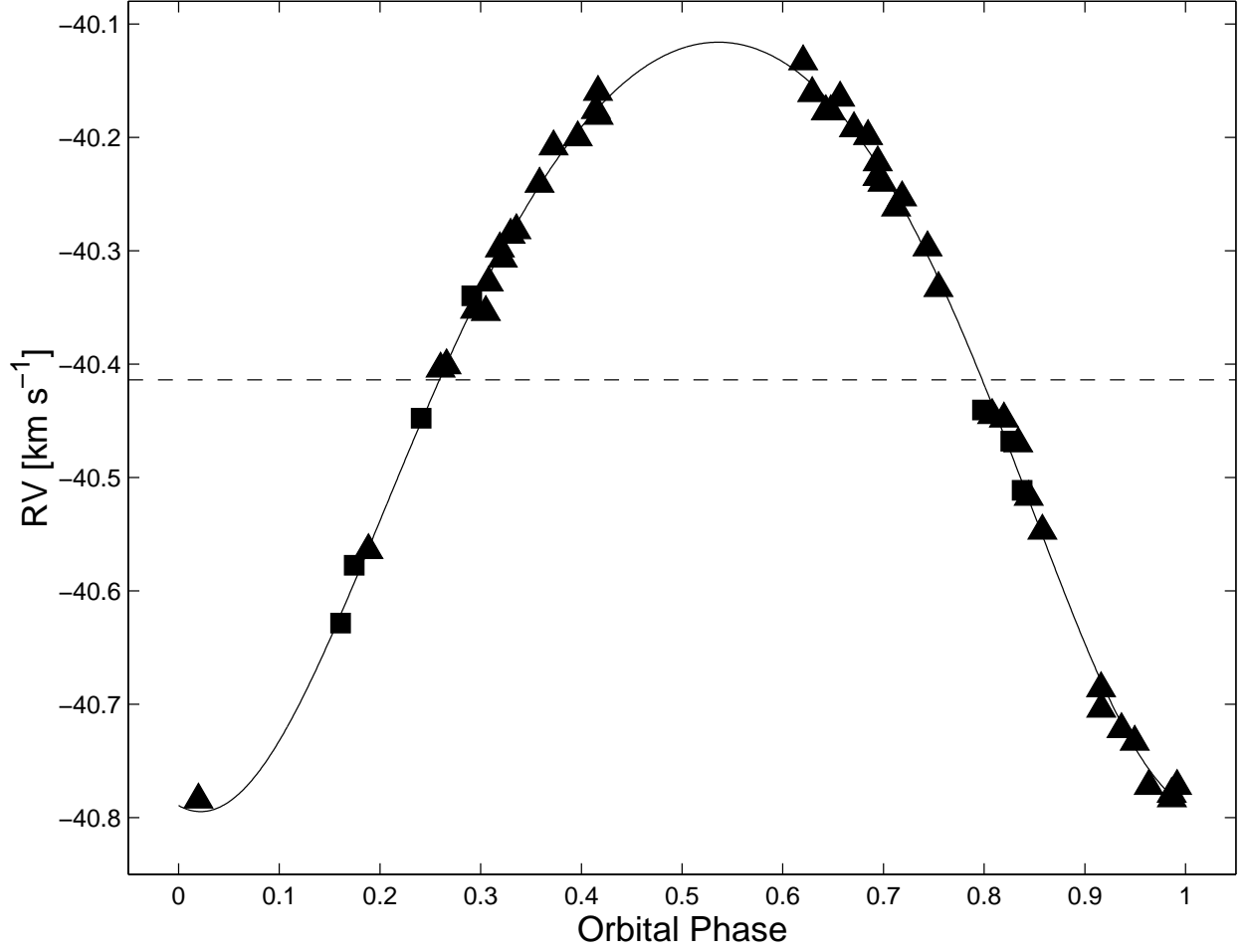


Fig. 3.— The radial velocities and the orbital fit as a function of phase. Triangles and squares: see Figure 1.

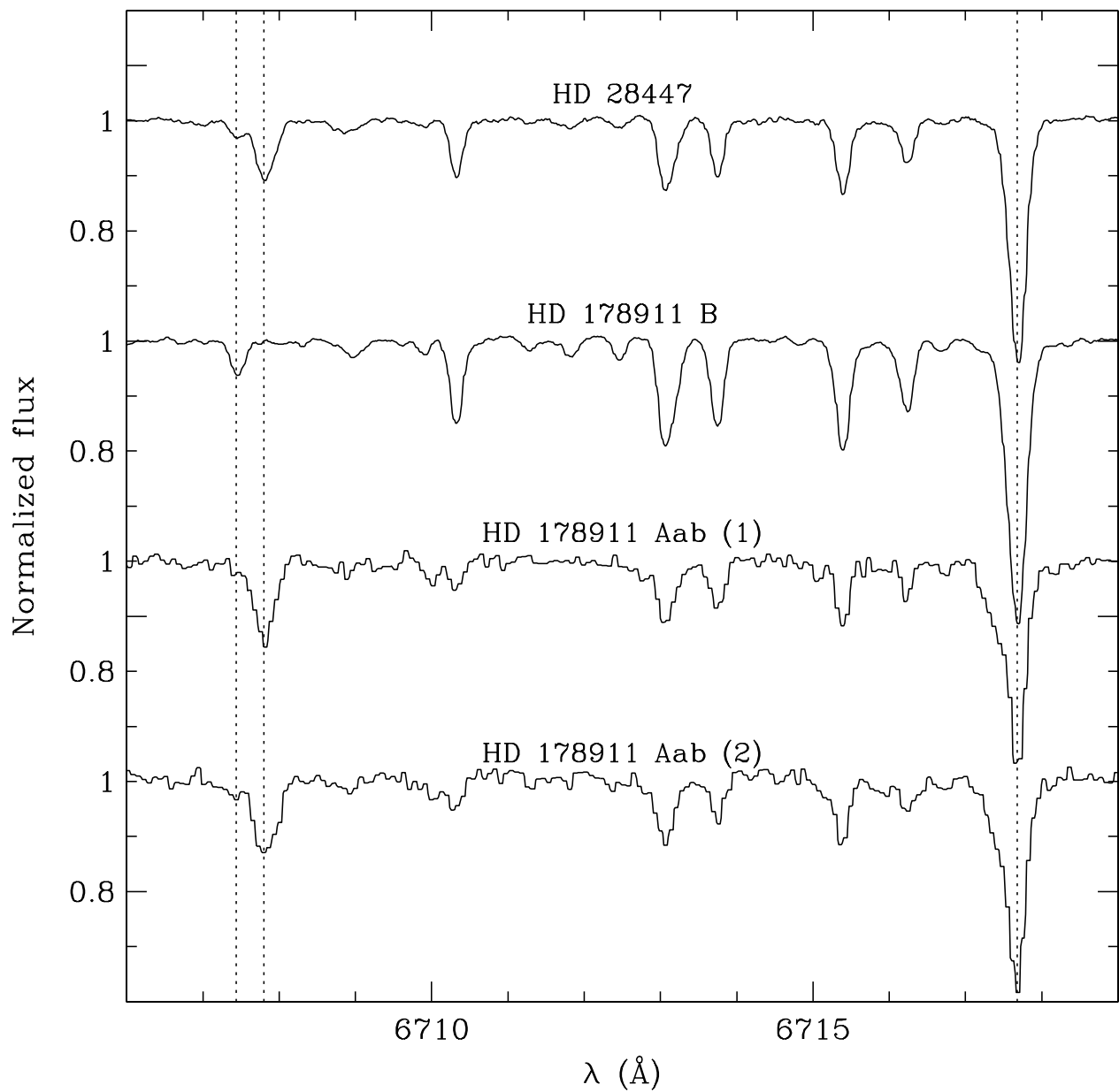


Fig. 4.— The  $\lambda$  6707.8 Å Li I line region in ELODIE spectra. Three spectral lines are marked by dotted lines in the Figure:  $\lambda$  6707.44 Å Fe I,  $\lambda$  6707.80 Å Li I and  $\lambda$  6717.68 Å Ca I.

Table 1.

JD-2400000	RV	Error	Instrument
	km s <sup>-1</sup>	km s <sup>-1</sup>	
51008.976	−40.511	0.013	H
51037.797	−40.448	0.012	H
51292.098	−40.440	0.012	H
51294.111	−40.468	0.010	H
51318.033	−40.628	0.008	H
51318.992	−40.577	0.010	H
51391.487	−40.564	0.010	E
51398.821	−40.340	0.014	H
51422.356	−40.133	0.010	E
51438.359	−40.517	0.008	E
51439.325	−40.547	0.009	E
51507.253	−40.445	0.009	E
51689.592	−40.241	0.008	E
51690.580	−40.208	0.009	E
51693.587	−40.176	0.009	E
51722.547	−40.448	0.009	E
51723.560	−40.470	0.010	E
51754.470	−40.401	0.009	E
51756.498	−40.352	0.008	E

Table 1—Continued

JD-2400000	RV	Error	Instrument
	km s <sup>-1</sup>	km s <sup>-1</sup>	
51757.458	−40.328	0.008	E
51758.456	−40.307	0.009	E
51759.424	−40.282	0.010	E
51780.438	−40.161	0.009	E
51781.406	−40.177	0.012	E
51782.405	−40.165	0.010	E
51783.394	−40.192	0.009	E
51784.393	−40.199	0.013	E
51785.421	−40.240	0.009	E
51786.393	−40.262	0.009	E
51789.396	−40.333	0.009	E
51802.384	−40.722	0.009	E
51803.323	−40.733	0.009	E
51804.329	−40.772	0.009	E
51806.327	−40.772	0.009	E
51808.347	−40.784	0.016	E
51835.272	−40.200	0.009	E
51853.240	−40.177	0.010	E
51858.294	−40.253	0.009	E

Table 1—Continued

JD-2400000	RV	Error	Instrument
	km s <sup>-1</sup>	km s <sup>-1</sup>	
51900.241	−40.354	0.018	E
51901.228	−40.298	0.014	E
51908.244	−40.181	0.022	E
51979.684	−40.160	0.010	E
52074.570	−40.297	0.008	E
52111.478	−40.404	0.010	E
52116.452	−40.286	0.008	E
52142.501	−40.235	0.009	E
52142.515	−40.222	0.009	E
52158.367	−40.686	0.014	E
52158.380	−40.704	0.013	E
52163.387	−40.779	0.011	E
52163.400	−40.783	0.012	E

Note. — H: HIRES, E: ELODIE. The HIRES velocities were shifted to the ELODIE zero-point.

Table 2. Best-fit orbital solution

$P$	(days)	$71.487 \pm 0.018$
$T$	(JD) <sup>†</sup>	$50\,305.70 \pm 0.62$
$e$		$0.1243 \pm 0.0075$
$\gamma$	(km s <sup>−1</sup> )	$-40.4138 \pm 0.0018$
$w$	(°)	$169.8 \pm 3.6$
$K_1$	(m s <sup>−1</sup> )	$339.3 \pm 3.1$
$\Delta\text{RV}_{\text{H-E}}$	(km s <sup>−1</sup> )	$-40.4886 \pm 0.0053$
$a_1 \sin i$	(10 <sup>−3</sup> AU)	$2.212 \pm 0.021$
$f_1(m)$	(10 <sup>−9</sup> M <sub>⊙</sub> )	$2.826 \pm 0.079$
$m_{2,\text{min}}$	(M <sub>Jup</sub> )	$6.292 \pm 0.059$
$N$		$44(\text{E}) + 7(\text{H})$
$\sigma_{\text{O-C}}$	(m s <sup>−1</sup> )	$11.0 \text{ (E:10.6, H:13.6)}$

<sup>†</sup>JD = HJD − 2 400 000

Table 3. The measured atmospheric parameters of HD 178911B

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$T_{\text{eff}}$	(K)	$5650 \pm 80$
$\log g$	(cgs)	$4.65 \pm 0.15$
$\xi_t$	(km s <sup>-1</sup> )	$0.85 \pm 0.19$
[Fe/H]		$0.28 \pm 0.08$
$W_\lambda(\text{Li})$	(mÅ)	$< 2.3$
$\log n(\text{Li})$		$< 0.75$
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